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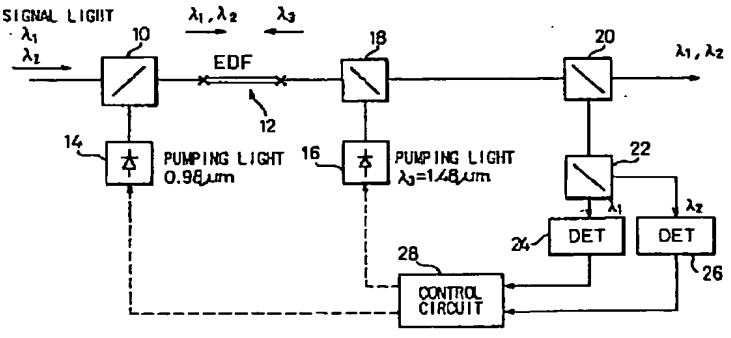
(54) Method and apparatus for controlling optical amplifier used for optically amplifying wavelength-division multiplexed signal

(57) A method and apparatus for controlling gain differences between optical signals, and hence an output of each individual optical signal, in an optical amplifier including a rare-earth-doped fiber for optically amplifying a wavelength-division multiplexed signal. Pumping light is injected into an erbium-doped fiber that is also supplied with additional pumping light that gives a different gain characteristic to the erbium-doped fiber. The output of each signal light is detected by a photodetector, and based on the detected output, injection power is controlled individually for each pumping light.

Fig.1



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Description

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a method and apparatus for controlling an optical amplifier containing a rare-earth-doped fiber for optically amplifying a wavelength-division multiplexed signal.

2. Description of the Related Art

Optical amplification systems using erbium-doped optical-fiber amplifiers have already been put to practical use, and to further increase transmission speed, developers are working toward the practical implementation of a multiple-wavelength simultaneous amplification system for wavelength-division multiplexed transmissions of multiple signals at different wavelengths through an optical transmission path including an optical amplifier. An optical amplifier for such a system is required to have the function of controlling gains at multiple signal wavelengths. Usually, for a single waveform, this could be accomplished by controlling pumping light, but in the case of multiple-wavelength simultaneous amplification, not only controlling pumping light but controlling gain differences between multiple signals also becomes necessary in order to control the gain of each individual signal.

U.S. Serial No. 508,471 (filed on July 28, 1995) proposes a method in which two pumping lights, one in the 0.98-μm band and the other in the 1.48-μm band, giving complementary gain characteristics (the relationship between signal light wavelength and gain), are simultaneously applied, attempting to achieve a flat gain characteristic and thereby reducing the gain difference between two signal wavelengths. However, no suggestions are made about controlling the gain difference and hence controlling the output of each individual optical signal.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide a method and apparatus for controlling gain differences between optical signals, and hence an output of each individual optical signal, in an optical amplifier used to optically amplify a wavelength-division multiplexed signal.

According to the present invention, there is provided a method of controlling an optical amplifier including a rare-earth-doped fiber for optically amplifying a wavelength-division multiplexed signal carrying a plurality of optical signals at different wavelengths, comprising the steps of: injecting first pumping light into the rare-earth-doped fiber; injecting second pumping light into the rare-earth-doped fiber, the second pumping light giving a different gain characteristic to the rare-earth-doped fiber from a gain characteristic that the first pumping light gives; and controlling an injection power for at least either one of the first and the second pumping light.

According to the present invention, there is also provided a method of controlling an optical amplifier including a rare-earth-doped fiber for optically amplifying a wavelength-division multiplexed signal carrying a plurality of optical signals at different wavelengths, comprising the steps of: injecting control light into the rare-earth-doped fiber, the control light being at a wavelength within a wavelength region where the rare-earth-doped fiber exhibits an optical amplification effect; and controlling the power or wavelength of the control light to be injected, thereby controlling a gain difference between the plurality of optical signals.

According to the present invention, there is also provided an apparatus for controlling an optical amplifier including a rare-earth-doped fiber for optically amplifying a wavelength-division multiplexed signal carrying a plurality of optical signals at different wavelengths, comprising: means for injecting first pumping light into the rare-earth-doped fiber; means for injecting second pumping light into the rare-earth-doped fiber, the second pumping light giving a different gain characteristic to the rare-earth-doped fiber from a gain characteristic that the first pumping light gives; and means for controlling an injection power for at least either one of the first and the second pumping light.

According to the present invention, there is also provided an apparatus for controlling an optical amplifier including a rare-earth-doped fiber for optically amplifying a wavelength-division multiplexed signal carrying a plurality of optical signals at different wavelengths, comprising: means for injecting control light into the rare-earth-doped fiber, the control light being at a wavelength within a wavelength region where the rare-earth-doped fiber exhibits an optical amplification effect; and means for controlling the power or wavelength of the control light to be injected, thereby controlling a gain difference between the plurality of optical signals.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a block diagram showing a first embodiment of the present invention;

Figure 2 is a block diagram showing a modified example of the first embodiment of the present invention;

Figure 3 is a graph for explaining the operation of the circuit shown in Figure 1;

Figure 4 is a graph showing the emission probability and absorption probability to erbium atoms in an erbium-doped fiber, and the ratio of the emission probability to the absorption probability as a function of wavelength;

Figure 5 is a graph showing the wavelength dependence of gain coefficient for various excitation ratios;

Figure 6 is a block diagram showing a second embodiment of the present invention;

Figure 7 is a block diagram showing a modified example of the second embodiment of the present invention; and

Figure 8 is a block diagram showing another modified example of the second embodiment of the present invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Figure 1 shows the configuration of an optical amplifier to which control according to a first embodiment of the invention is applied. In Figure 1, signal light consisting of two different wavelengths, λ_1 and λ_2 ($\lambda_1 < \lambda_2$), is combined in a beam combiner (optical coupler) 10 with pumping light (for example, at 0.98 μm wavelength) from a light source 14, and enters an erbium-doped fiber 12. Pumping light from a light source 16 emitting at wavelength λ_3 (for example, λ_3 = 1.48 μm) is introduced by a beam combiner (optical coupler) 18 into the erbium-doped fiber 12 in the direction opposite to the direction of the signal light. Some of the signal light amplified through the erbium-doped fiber 12 is separated by an optical coupler 20 and enters a beam splitter 22 where the light is split into wavelengths λ_1 and λ_2, whose optical powers are detected by photodetectors 24 and 26, respectively. Based on the detection outputs from the photodetectors 24 and 26, a control circuit 28 controls drive currents to the light sources 14 and 16, thus controlling the optical power.

It will be appreciated that the injection direction of each pumping light is not limited to that shown in the illustrated example. Further, instead of controlling the drive currents to the light sources 14 and 16 to control the injection powers of the respective pumping lights, variable attenuators 15 and 17 may be provided between the light source 14, 16 and the beam combiners 10, 18, as shown in Figure 2, and the degree of attenuation in the variable attenuators 15 and 17 may be controlled to control the injection powers of the pumping lights.

As shown in Figure 15 given in Japanese Patent Application No. 6-229164, with the pumping light in the 0.98-μm band the gain is higher at the shorter wavelength than at the longer wavelength, whereas with the pumping light in the 1.48-μm band the gain is higher at the longer wavelength than at the shorter wavelength. The control circuit 28 calculates optical outputs at λ_1 and λ_2 from the outputs of the photodetectors 24 and 26, and if the optical output power P_1 at the shorter wavelength λ_1 is larger than the optical output power P_2 at the longer wavelength λ_2, it reduces the power of the 0.98-μm pumping light that is contributing to a higher gain at the shorter wavelength and increases the power of the 1.48-μm pumping light that has the effect of increasing the gain at the shorter wavelength. Conversely, if P_2 is larger than P_1, the power of the 1.48-μm pumping light is reduced, while the power of the 0.98-μm pumping light is increased. Furthermore, if the combined optical output power of the two optical signals is smaller than a desired output power, the pumping light powers in both the 0.98-μm and 1.48-μm bands are raised, and if the combined optical output power is larger than the predetermined output power, both pumping light powers are reduced so that the desired optical output can be obtained.

As described, according to the first embodiment of the invention, the pumping light powers in the 0.98-μm and 1.48-μm bands are adjusted while monitoring the output of each optical signal so that the desired output can be obtained for each optical signal.

Figure 3 shows the results of an experiment conducted with each input signal optical power at -8.1 dBm and input signal light wavelengths at λ_1 = 1535 nm and λ_2 = 1558 nm. In Figure 3, the relationship between the 0.98-μm pumping light power and 1.48-μm pumping light power is shown for a constant gain difference ΔG (= $P_{1558} - P_{1535}$) at 0 and at +1 dB, and a constant total output (= $P_{1558} + P_{1535}$) at 11, 12, 13, and 13.5 dBm. For example, it is shown that for ΔG = 0, a total output of 13 dBm is obtained when the 0.98-μm and 1.48-μm pumping light powers are set at 40 mW and 15 mW, respectively, and a total output of 13.5 dBm at 30 mW and 35 mW. In this way, by varying the 0.98-μm pumping light power and 1.48-μm pumping light power along the curve of ΔG = 0, the optical output can be varied while maintaining the gain difference constant at 0.

Figure 4 shows an emission probability (the probability of emission transition) and absorption probability (the probability to absorption transition) for an erbium-doped fiber, and the ratio of the emission probability to the absorption probability as a function of wavelength. As is shown in Figure 4, emission just occurs at 1.48 μm (1480 nm) and the excitation ratio (the ratio of erbium atoms in excited state) is decreasing. However, since the emission ratio is low, light at this wavelength is not amplified. It is shown, however, that at longer wavelengths the emission ratio increases, with the excitation ratio further decreasing.

Figure 5 is a graph showing how the wavelength dependence of gain coefficient changes for various excitation ratios. It can be seen from Figure 5 that at excitation ratios closer to 1.0 the gain is relatively large at the shorter wavelength (for example, λ_1 = 1.54 μm), the gain becoming relatively large at the longer wavelength (for example, λ_1 = 1.55 μm) as the excitation ratio decreases.

From the above, it can be deduced that control of the gain difference was possible with the 0.98-μm/1.48-μm hybrid pumping because emission occurs at 1.48 μm, causing the excitation ratio to decrease. However, it can also be seen that as long as a wavelength band, such as 1.48 μm, which is not amplified in an erbium-doped fiber, is used, there is a limit to the decrease of the excitation ratio, limiting the control range.

Accordingly, in a second embodiment of the

present invention, light at a wavelength falling within the operating wavelength band of a rare-earth-doped fiber is used as control light, the wavelength preferably being in a wavelength region where the emission probability is greater than the absorption probability, and more preferably not shorter than 1520 nm, and by controlling the optical power or wavelength of this control light, the excitation ratio is controlled, thereby controlling gain differences between signals.

Figure 6 shows the configuration of an optical amplifier to which control according to the second embodiment of the invention is applied. In Figure 6, signal light consisting of two different wavelengths, λ_1 and λ_2 (for example, λ_1 = 1.54 μm and λ_2 = 1.55 μm, as shown in Figure 5), is combined in a beam combiner 10 with pumping light (for example, 0.98 μm wavelength light) from a light source 14, and enters an erbium-doped fiber 12. Control light from a light source 40 emitting at wavelength λ_3 (for example, λ_3 = 1.57 μm, as shown in Figure 5) is introduced, by a beam combiner 18, into the erbium-doped fiber 12 in the direction opposite to the direction of the signal light. Some of the signal light amplified through the erbium-doped fiber 12 is separated by an optical coupler 20 and enters a beam splitter 22 where the light is split into wavelengths λ_1 and λ_2, whose optical powers are detected by photodetectors 24 and 26, respectively. Based on the detection outputs from the photodetectors 24 and 26, a control circuit 28 controls the optical power or emitting wavelength of the light source 40 to control the gain difference, and controls the optical power of the light source 14 to control the overall (average) gain. In this manner, the output levels of the signal wavelengths λ_1 and λ_2 can be controlled at constant values.

It will be appreciated that the injection directions of the pumping light and control light are not limited to those shown in the illustrated example. Further, if it is required to remove the control light λ_3, an optical filter for removing the control light can be provided at the output. Controlling the optical power of the control light can be accomplished, for example, by controlling the drive current to a laser diode used as the light source 40. If the wavelength of the control light is to be controlled, a variable-wavelength laser, for example, is used as the light source 40.

Instead of introducing control light separate from the signal light, the gain difference between the signals can be controlled by controlling the power of signal light input to an optical amplifier 30 containing an erbium-doped fiber by using a variable attenuator 32, as shown in Figure 7. Since signal light is always set at a wavelength where a certain degree of emission probability is obtained, the gain difference can also be controlled by controlling the incident power of the signal light itself. Alternatively, as shown in Figure 8, the power of the signal light entering an optical amplifier 30 provided at the receiving end of an optical transmission path 34 may be controlled by using a variable attenuator 32 provided at the transmitting end.

Furthermore, in Figure 6, it is possible to transmit the control light together with the signal light of λ_1 and λ_2 by modulating the control light with a supervisory (SV) signal used to supervise the transmission path. In this case, it is desirable that the control light be introduced into the erbium-doped fiber in the same direction as the direction of the signal light.

Claims

1. A method of controlling an optical amplifier including a rare-earth-doped fiber for optically amplifying a wavelength-division multiplexed signal carrying a plurality of optical signals at different wavelengths, comprising the steps of:

   injecting first pumping light into the rare-earth-doped fiber;
   injecting second pumping light into the rare-earth-doped fiber, the second pumping light giving a different gain characteristic to the rare-earth-doped fiber from a gain characteristic that the first pumping light gives; and
   controlling an injection power for at least one of the first and the second pumping lights.

2. A method according to claim 1, further comprising the step of detecting respective powers of the plurality of optical signals at an output of the optical amplifier, wherein, in the controlling step, the injection powers of the first and the second pumping lights are controlled in accordance with the detected optical signal powers.

3. A method according to claim 2, wherein, in the controlling step, the injection powers of the first and the second pumping lights are controlled by controlling drive currents to the light sources of the first and the second pumping lights.

4. A method according to claim 2, wherein, in the controlling step, the injection powers of the first and the second pumping lights are controlled by controlling a variable optical attenuator provided between the rare-earth-doped fiber and each of the light sources of the first and the second pumping lights.

5. A method of controlling an optical amplifier including a rare-earth-doped fiber for optically amplifying a wavelength-division multiplexed signal carrying a plurality of optical signals at different wavelengths, comprising the steps of:

   injecting control light into the rare-earth-doped fiber, the control light being at a wavelength within a wavelength region where the rare-earth-doped fiber exhibits an optical amplification effect; and
   controlling injection power or wavelength of the

control light, thereby controlling a gain difference between the plurality of optical signals.

6. A method according to claim 5, wherein the wavelength of the control light is different from the wavelength of any one of the plurality of optical signals.

7. A method according to claim 6, wherein the wavelength of the control light falls within a wavelength region where an emission probability in the rare-earth-doped fiber is greater than an absorption probability.

8. A method according to claim 7, wherein the rare-earth-doped fiber is an erbium-doped fiber, and the wavelength of the control light is equal to or longer than 1520 nm.

9. A method according to claim 8, wherein the wavelengths of the plurality of optical signals are within a range from 1530 to 1565 nm, and the wavelength of the control light is equal to or longer than 1565 nm.

10. A method according to claim 6, further comprising the step of removing the control signal at an output of the optical amplifier.

11. A method according to claim 6, wherein the control light is modulated with a supervisory signal used to supervise a transmission channel.

12. A method according to claim 5, wherein the control signal is the wavelength-division multiplexed signal itself.

13. A method according to claim 5, further comprising the step of detecting respective powers of the plurality of optical signals at an output of the optical amplifier, wherein, in the controlling step, the injection power or wavelength of the control light is controlled in accordance with the detected optical signal powers.

14. An apparatus for controlling an optical amplifier including a rare-earth-doped fiber for optically amplifying a wavelength-division multiplexed signal carrying a plurality of optical signals at different wavelengths, comprising:

a first optical coupler for injecting first pumping light into the rare-earth-doped fiber;
a second optical coupler for injecting second pumping light into the rare-earth-doped fiber, the second pumping light giving a different gain characteristic to the rare-earth-doped fiber from a gain characteristic that the first pumping light gives; and
a control circuit for controlling an injection power of at least one of the first and the second pumping lights.

15. An apparatus according to claim 14, further comprising means for detecting respective powers of the plurality of optical signals at an output of the optical amplifier, wherein the control circuit controls the injection powers of the first and the second pumping lights in accordance with the detected optical signal powers.

16. An apparatus according to claim 15, wherein the control circuit controls the injection powers of the first and the second pumping lights by controlling drive currents to light sources of the first and the second pumping lights.

17. An apparatus according to claim 15, wherein the control circuit controls the injection powers of the first and the second pumping lights by controlling a variable optical attenuator provided between the rare-earth-doped fiber and each of light sources of the first and the second pumping light.

18. An apparatus for controlling an optical amplifier including a rare-earth-doped fiber for optically amplifying a wavelength-division multiplexed signal carrying a plurality of optical signals at different wavelengths, comprising:

an optical coupler for injecting control light into the rare-earth-doped fiber, the control light being at a wavelength within a wavelength region where the rare-earth-doped fiber exhibits an optical amplification effect; and
a control circuit for controlling injection power or wavelength of the control light, thereby controlling a gain difference between the plurality of optical signals.

19. An apparatus according to claim 18, wherein the wavelength of the control light is different from the wavelength of any one of the plurality of optical signals.

20. An apparatus according to claim 19, wherein the wavelength of the control light falls within a wavelength region where an emission probability in the rare-earth-doped fiber is greater than an absorption probability.

21. An apparatus according to claim 20, wherein the rare-earth-doped fiber is an erbium-doped fiber, and the wavelength of the control light is equal to or longer than 1520 nm.

22. An apparatus according to claim 21, wherein the wavelengths of the plurality of optical signals are within a range from 1530 to 1565 nm, and the wavelength of the control light is equal to or longer than

1565 nm.

23. An apparatus according to claim 19, further comprising means for removing the control signal at an output of the optical amplifier.

24. An apparatus according to claim 19, wherein the control light is modulated with a supervisory signal used to supervise a transmission channel.

25. An apparatus according to claim 18, wherein the control signal is the wavelength-division multiplexed signal itself.

26. An apparatus according to claim 18, further comprising means for detecting the respective powers of the plurality of optical signals at an output of the optical amplifier, wherein the control circuit controls the injection power or wavelength of the control light in accordance with the detected optical signal powers.

Fig. 1

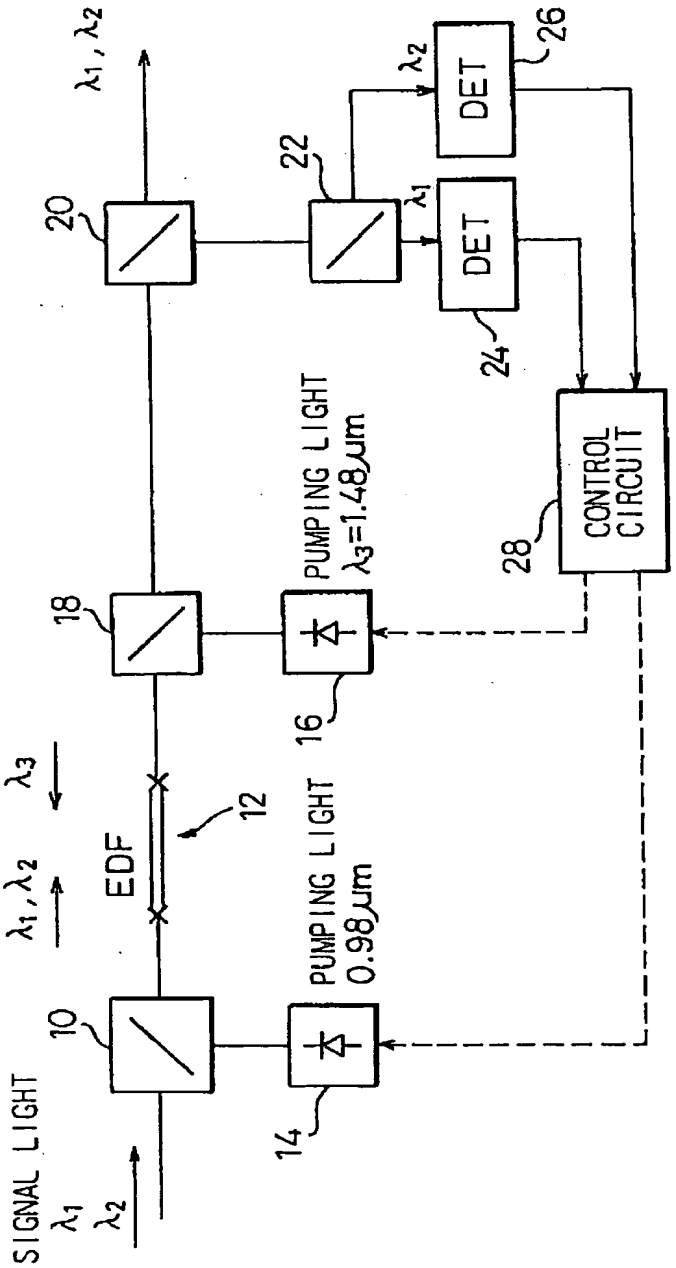
SIGNAL LIGHT
λ1
λ2
10
λ1, λ2
EDF
12
λ3
PUMPING LIGHT
0.98μm
14
16
18
PUMPING LIGHT
λ3=1.48μm
20
λ1, λ2
22
λ2
DET
26
λ1
DET
24
CONTROL CIRCUIT
28

Fig.2

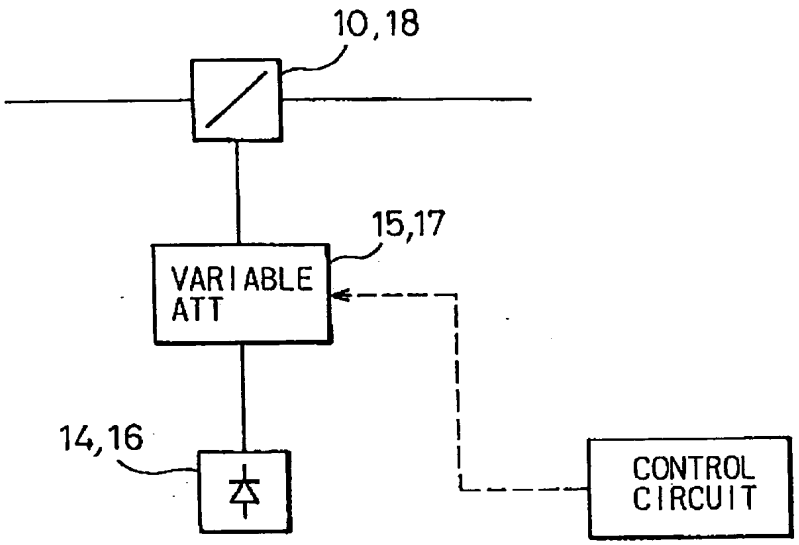
10,18
15,17
VARIABLE ATT
14,16
CONTROL CIRCUIT

Fig.3

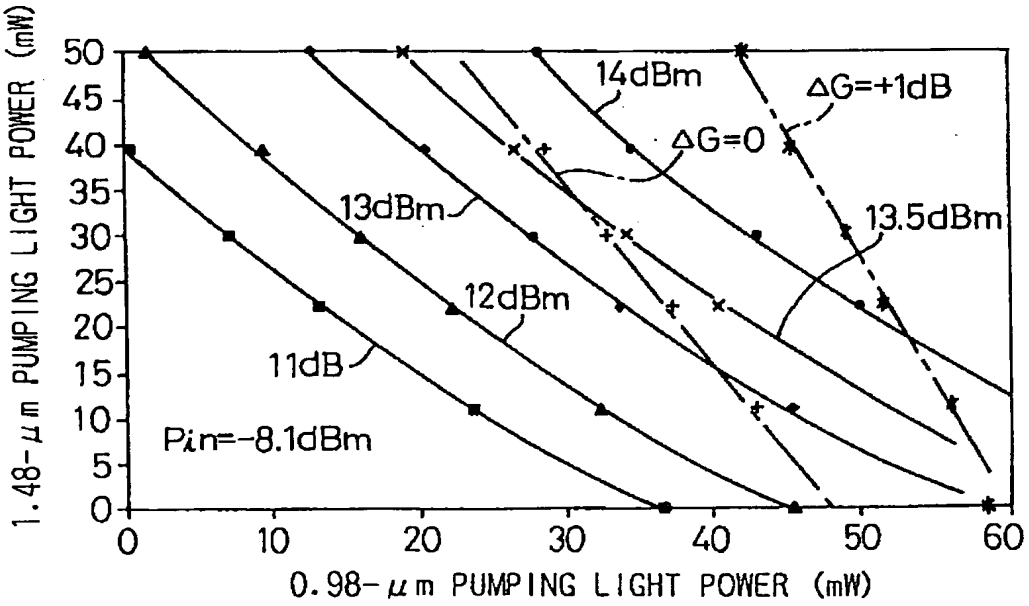
1.48-μm PUMPING LIGHT POWER (mW)
0.98-μm PUMPING LIGHT POWER (mW)
14dBm
ΔG=+1dB
ΔG=0
13dBm
13.5dBm
12dBm
11dB
Pin=-8.1dBm
0
5
10
15
20
25
30
35
40
45
50
60

Fig.4

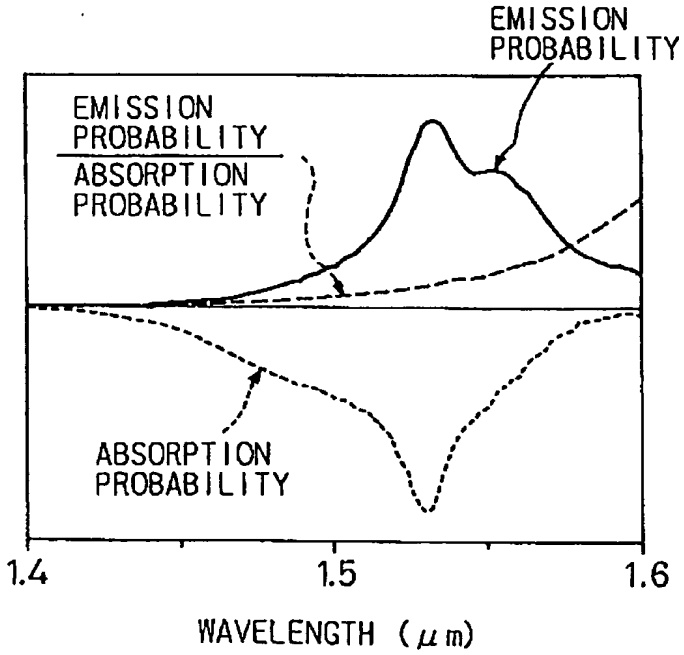
EMISSION
PROBABILITY
EMISSION
PROBABILITY
ABSORPTION
PROBABILITY
ABSORPTION
PROBABILITY
1.4
1.5
1.6
WAVELENGTH (μm)

Fig.5

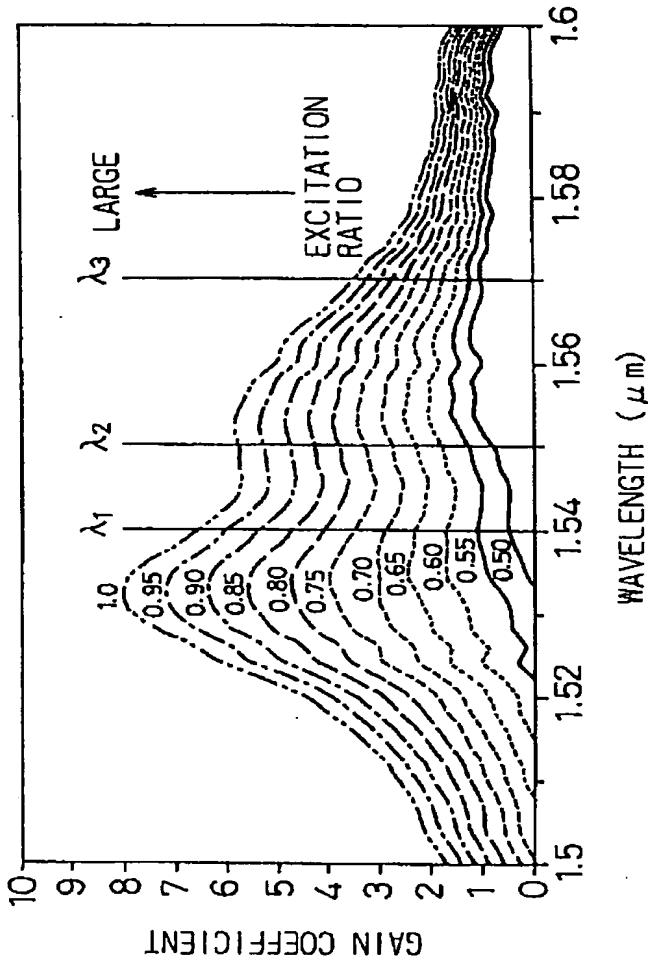
GAIN COEFFICIENT
WAVELENGTH (μm)
λ1
λ2
λ3 LARGE
EXCITATION RATIO
1.0
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
10
9
8
7
6
5
4
3
2
1
0
1.5
1.52
1.54
1.56
1.58
1.6

Fig.6

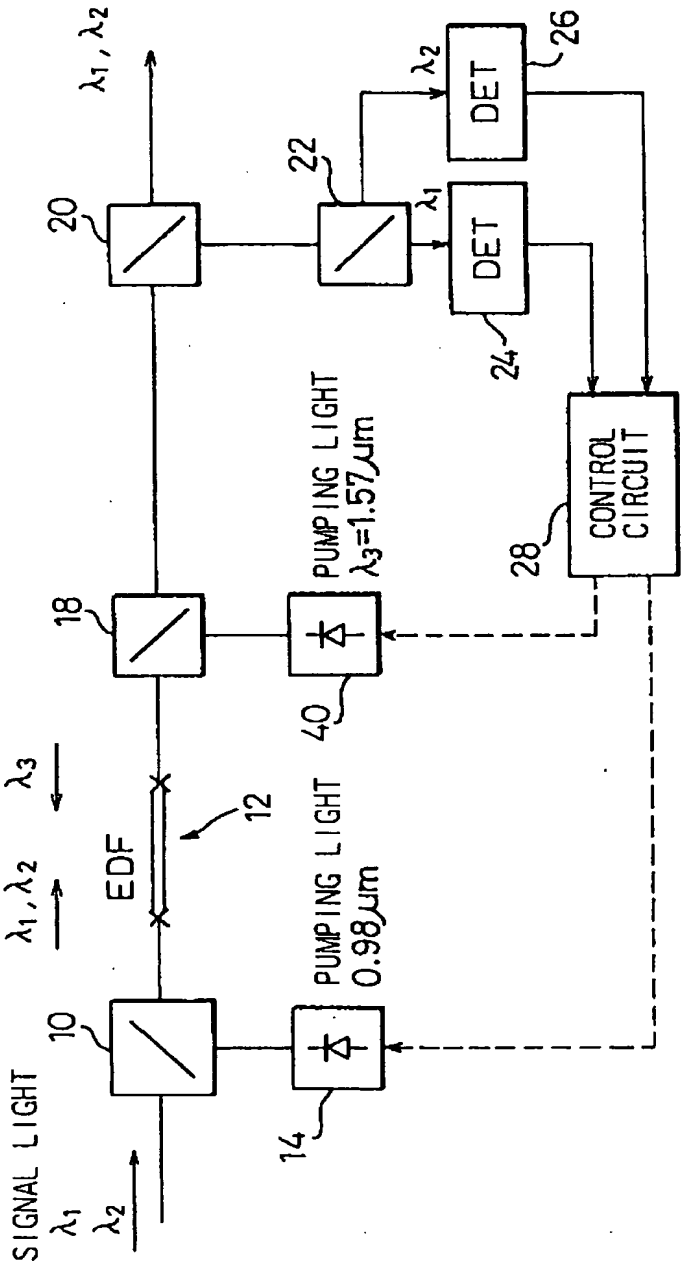
SIGNAL LIGHT
λ1
λ2
10
λ1, λ2
EDF
12
λ3
PUMPING LIGHT
0.98μm
14
18
PUMPING LIGHT
λ3=1.57μm
40
20
λ1, λ2
22
λ2
DET
26
λ1
DET
24
CONTROL CIRCUIT
28

Fig.7

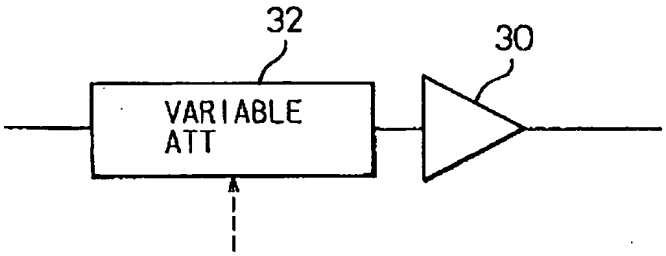
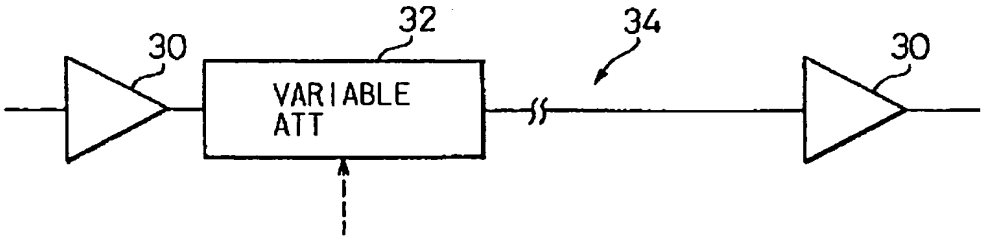
Fig.8